Sub-picosecond pulse generation by 40-GHz passively mode-locked quantum-dash 1-mm-long Fabry-Pérot laser diode

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Abstract: Optical pulses at a repetition rate of 39.8 GHz have been observed in a dc-biased passively mode-locked quantum-dash Fabry-Pérot laser diode. The pulses generated by this diode are studied in the temporal and spectral domains using a second harmonic generation frequency-resolved optical gating system. By using a tunable band-pass filter, it is observed that the pulse width decreases as the number of lasing modes selected by the filter increases. Furthermore, by controlling the phase difference of the modes using a 450m-long single mode fibre, a passive compression of the pulses is obtained. A minimum pulse width of 720 fs has been measured with this type of mode-locked Fabry-Pérot laser.

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References and links

1. E. U. Rafailov, M. A. Catalune, W. Sibbet, N. D. Il'inskaya, Yu. M. Zadiranov, A. E. Zhukov, V. M. Ustinov, D. A. Livshits, A. R. Kovsh and N. N. Ledenstsov, "High-power picosecond and femtosecond pulse generation from a two-section mode-locked quantum-dot laser," Appl. Phys. Lett. **87**, 081107 (2005).
2. Y.-C. Xin, D. J. Kane and L. F. Lester. "Frequency-resolved optical gating characterisation of passively mode-locked quantum-dot laser," Electron. Lett. **44**, 1255-1257 (2008).
3. C. Gosset, K. Merghem, A. Martinez, G. Moreau, G. Patriarche, G. Aubin, J. Landreau, F. Lelarge and A. Ramdame. "Subpicosecond pulse generation at 134 GHz and low radiofrequency spectral linewidth in quantum dash-based Fabry-Perot lasers emitting at 1.5 μm," Electron. Lett. **42**, 91-92 (2006).
4. G.-H. Duan. "Optical signal processing using InP-based quantum-dot semiconductor mode-locked lasers," *in Proceedings of CLEO'08*, CMG3 (2008).
5. A. Shen, J.-G. Provost, A. Akrout, B. Rousseau, F. Lelarge, O. Legouezigou, F. Pommereau, F. Poingt, L. Legouezigou, G.-H. Duan, and A. Ramdane. "Low confinement factor quantum dash (QD) mode-locked Fabry-Pérot (FP) laser diode for tunable pulse generation," *in Proceedings of OFC'08,* OThK1 (2008).
6. K. Merghem, A. Akrout, A. Martinez, G. Aubin, A. Ramdane, F. Lelarge and G.-H. Duan. "Pulse generation at 346 GHz using passively mode locked quantum-dash-based laser at 1.55 μm," Appl. Phys. Lett. **94**, 021107 (2009).
7. F. Lelarge, B. Dagens, J. Renaudier, R. Brenot, A. Accard, F. van Dijk, D. Make, O. Le Gouezigou, J.-G. Provost, F. Poingt, J. Landreau, O. Drisse, E. Derouin, B. Rousseau, F. Pommereau, and G.-H. Duan. "Recent advances on InAs/InP quantum dash based semiconductor lasers and optical amplifiers operating at 1.55 μm," J. Sel. Top. Quantum Electron. **13**, 111-124 (2007).
8. G. P. Agrawal, "Nonlinear fiber optics," (Academic Press, Second Edition, 1995).
9. J. Renaudier, G.-H. Duan, P. Landais, and P. Gallion, "Phase Correlation and Linewidth Reduction of 40 GHz Self-Pulsation in Distributed Bragg Reflector Semiconductor Lasers," J. Quantum Electron. **43**, 147-156 (2007).

1. Introduction

Quantum-dot and quantum-dash mode-locked lasers (QD-MLL) have recently attracted much interest due to their potential applications for optical time-domain multiplexing, all-optical clock-recovery and all-optical waveform generation. Regarding the latter application, pulse generation has been demonstrated using two-section devices composed of an absorber and a gain section. Rafailov *et al* [1] have studied the generation of 2 ps auto-correlated pulses at 21 GHz repetition rate using a two-section mode-locked quantum-dot laser. In this case, the length of the gain section is 1.8 mm and the absorber section is 0.3 mm. Xin and co-workers [2] have reported on 5 to 6.3 ps pulses at a repetition rate of 5 GHz. The laser under test is a two-section passive mode-locked quantum-dot laser composed of a 1 mm absorber and 7.3 mm gain section. In those two works, the devices under test exhibit an optical spectrum centered around 1200 nm, with a full-width at half maximum (FWHM) of 14 nm and 4.3 nm, respectively. On the other hand, pulse generation has also been studied using Fabry-Pérot (FP) quantum-dot MLL lasers operating at 1550 nm. Gosset *et al* [3] have reported on 1.1 and 2 ps auto-correlated pulses at repetition rates of 134 and 42 GHz, respectively. The analyzed device is a one-section 340 μm-long quantum-dash laser whose optical spectrum presents a FWHM of 4.3 nm. Investigations on the characteristics of the QD-MLL structure, such as the confinement factor, have also been addressed in order to generate short pulses at 40 GHz with a reduced radio-frequency (RF) linewidth [4]. Furthermore, 8 ps pulses at a repetition rate of 10 GHz have been reported on actively mode-locked quantum-dash single-section lasers with a cavity length of 4.2 mm and optimized optical confinement factor [5]. In this case, insights on the phase-locking of the optical modes were provided by using a band-pass optical filter at the laser output. More recently, optimized structures of QD-MLL with active regions varying from 170 to 120 μm have been studied for pulse generation at repetition rates from 245 to 346 GHz, respectively [6].

The aim of our work is to perform a deeper experimental analysis on all-optical pulse generation by using a dc-biased passively mode-locked QD-FP single-section laser. We analyze both the pulse width and instantaneous frequency variation (chirp) of an optically generated signal at a repetition rate of 39.8 GHz by the QD-MLL under test. This study is performed in terms of the optical modes passing through a variable band-pass filter at the laser output. From our experimental results it is observed that the width of the optically generated pulses follows a decreasing trend as the number of optical modes passing through the filter increases. This behavior may imply that the majority of the optical modes are well passively phase-locked, as opposed to previous analysis performed on similar laser structures where it has been observed a poor phase-locking for a broad filter bandwidth in comparison to the phase-locking obtained for a narrower filter [5].

Finally, owing to the initial chirp exhibited by the optically generated pulses and the group velocity dispersion in a single mode fibre (SMF), pulses are passively compressed after its propagation through a given piece of such fibre. Thus, we experimentally demonstrate the generation of pulses as short as 720 fs with a repetition rate of 39.8 GHz by a dc-biased and passively mode-locked QD-FP laser diode.

2. Experiment

Our device under test (DUT) is a 1-mm-long, dc-biased, multi-mode Fabry-Pérot quantum-dash semiconductor laser diode. The QD-based heterostructure is grown by gas source molecular beam epitaxy (GS-MBE) on S-dopped InP wafer. The active core consists of 6 layers of InAs-QD enclosed within 40-nm-thick InGaAsP barriers. The whole active structure is sandwiched within two 80-nm-thick separate confinement heterostructure layers (SCH). Both SCH and barriers are un-doped. Typical dimension along the growth axis and width of the QD to achieve emission at 1.55 μm are 2 nm and 20 nm, respectively. The density of dots per layer is

$2x10^{10}$ cm^{-2}. The DUT is a single-section device, without phase or saturable absorber sections. Further information on this type of device can be found in [7].

Typical optical power collected in a 1-m-long single mode fibre versus bias current for the analyzed DUT is shown in Fig. 1. The collected light is recorded on a slow response optical power meter as a function of the increasing and decreasing bias current. It presents a bias threshold of 18 mA and a total collected power of 4 mW when operating at 400 mA and temperature controlled at 25°C.

The collected optical spectrum is shown in Fig. 2(a). It exhibits more than 30 longitudinal modes, 0.31 nm apart, giving an optical FWHM-bandwidth of 12 nm centered at 1526 nm. The average optical linewidth of each longitudinal mode is measured at 80 MHz with an optical spectrum analyzer set at a resolution of 20 MHz.

Based on the optical power-versus-bias characterization, no hysteresis behavior is observed on this DUT. Furthermore, with such an optical mode-separation (0.31 nm), a beat-note (or RF-signal) is measured at 39.8 GHz as shown in Fig. 2(b). The RF-signal is obtained with no direct or external modulation applied to the laser. The measurement has been performed by using a fast response photo-detector connected at the DUT output and an electrical spectrum analyzer set at 10 MHz span and 5 kHz video bandwidth. A Lorentzian lineshape with a FWHM-linewidth of 25 kHz (limited to the instrument resolution) is measured from this RF-signal.

It is worth mentioning that considering the number of longitudinal modes selected by a Fabry-Pérot cavity (i.e. without considering the power distribution among the modes), an important signature of the passive mode-locking mechanism is a reduction of the linewidth associated to the RF-signal in comparison to the sum of the spectral linewidths corresponding to all the optical modes. In our analyzed device, an RF-linewidth of 25 kHz is by far smaller than
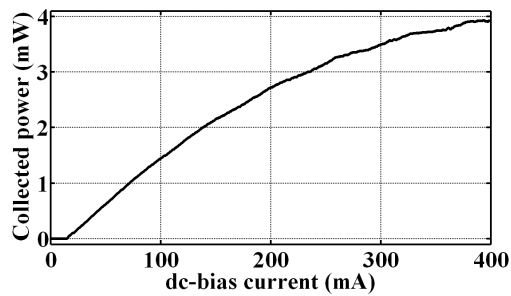

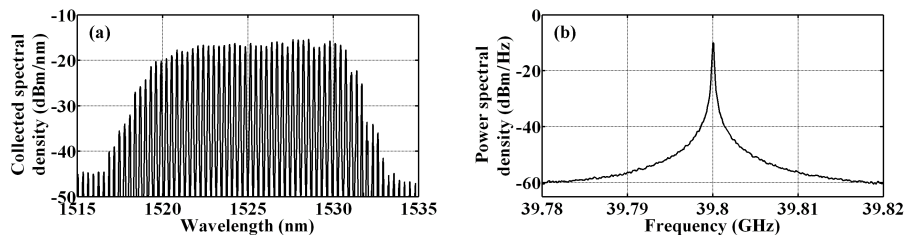Fig. 1. Optical power collected in a single mode fibre as a function of the dc-bias current.

Fig. 2. Optical spectra collected from the QD-PML FP laser under test (a) and RF generated signal (b), both of them at an operating dc-bias of 350 mA. The resolution of the optical and electrical spectrum analyzers are set to 20 MHz and 5 kHz, respectively.

the 80 MHz linewidth associated to any longitudinal mode and therefore to the sum of all the optical modes. This proves that our DUT is, indeed, a passively mode-locked semiconductor laser diode.

The experimental setup to study the performance of the passively mode-locked laser in the spectral and temporal domains is depicted in Fig. 3. The main components in this setup are an isolator (ISO), an Erbium doped fibre amplifier (EDFA) and a second harmonic generation (SHG) Frequency-Resolved Optical Gating (FROG) system. Once the output of the QD-PML FP laser is coupled to a 1-m-long SMF, the ISO is placed to suppress back-reflections whilst the EDFA enhances the power of the optical modes emitted from the laser. Furthermore, the SHG-FROG system allows the analysis of both pulse shape and instantaneous frequency variation to be implemented. The temporal and wavelength resolutions of the FROG system are 100 fs and 0.02 nm, respectively. In addition to these components, a variable band-pass optical filter (BPF) is utilized to select some lasing modes at the laser output. Moreover, owing to the initial chirp exhibited by the optically generated pulses and the group velocity dispersion effect, a 450-m long SMF is connected at the FROG input in order to compensate for the initial pulse chirp. Therefore, a passive pulse compression scheme is implemented. As a matter of fact, all the measurements are obtained with and without the inclusion of the 450-m SMF, allowing the analysis of the passive pulse compression to be performed.

Thus, the experiment is firstly achieved by measuring the time-width of the optically generated pulses in terms of the band-pass filter bandwidth whilst the dc-bias current is set to a constant value. Secondly, the time-width is measured in terms of the dc-bias current supplied to the QD-PML FP laser for various BPF bandwidths. Due to the restrictions imposed by the central wavelength of the BPF and the bandwidth of the EDFA, the filter is tuned at a central wavelength of 1530 nm and its bandwidth varies between 1 nm and 6 nm. Furthermore, it is worth mentioning that in our experimental study, the potential distortion introduced by the EDFA on the power and the phase of each lasing mode has been present in all our measurements. Therefore any change on the pulse width measured from the 450-m SMF fibre and the BPF are independent from the EDFA response.

3. Results

The analysis starts by measuring the pulse shape and chirp of the optically-generated pulses in terms of the BPF bandwidth. The shape of the retrieved pulses from the FROG system for filter bandwidths of 2 and 6 nm, before their propagation through the SMF, are shown in Figs. 4(a) and 4(b) (continuous line). In this case, pulses have a FWHM-width of 3.6 and 2.6 ps, respectively. Furthermore, at the FWHM-leading and -trailing edges, pulses exhibit a positive chirp ranging from -18 GHz to +25 GHz, and from -28 GHz to far above +50 GHz, respectively (see Figs. 4(c) and 4(d), continuous line).

As it was previously mentioned, in order to compensate for this initial positive chirp, a passive pulse compression approach based on group velocity dispersion in a SMF is implemented [8]. A piece of 450-m long SMF lying in between the EDFA and FROG system is considered. In all our measurements, we use a single mode fibre presenting a dispersion parameter equal to
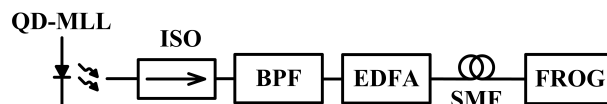

Fig. 3. Schematic of the experimental setup.

$-20 \, ps/nm \cdot km$ at 1530 nm. The retrieved pulses after their propagation through this piece of SMF are depicted in Figs. 4(a) and 4(b), broken lines. Despite the initial chirp not being completely canceled out (see Figs. 4(c) and 4(d), broken lines), compressed pulses are obtained after their propagation through the SMF. Particularly, for a filter bandwidth of 2 nm, a negative chirp is obtained after pulse propagation, ranging from +12 GHz to -8 GHz. Conversely, the chirp for a filter bandwidth of 6 nm is reduced to a value of +5 GHz at the FWHM-leading edge of the compressed pulse. At these conditions of 2 and 6 nm filter bandwidths, pulse widths of 2.1 and 1.25 ps are obtained, respectively. This provides pulse compression ratios approximately equal to 2. It should be noticed that chirp compensation and passive pulse compression can be further improved by using a piece of SMF with an optimum length [8]. For uncompressed pulses of 6 to 2 ps obtained at the output of the QD-PML FP laser, we estimate optimum lengths of the SMF ranging from 50 to 500 m, respectively.

The width of the retrieved pulses from the FROG system for filter bandwidths ranging from 1 nm to 6 nm is depicted in Fig. 5. In this case, there have been considered pulses before and after their propagation through a piece of a given SMF lying in between the EDFA and the FROG system. Moreover, retrieved pulses for an unfiltered optical spectrum are also shown, i.e. the full 12 nm optical bandwidth of the QD-PML FP laser is injected into the FROG system. From our experimental results it is observed that the width of the generated pulses decreases as the filter bandwidth increases. The broadest pulse of ∼6 ps is obtained when the filter suppresses most of the optical modes by setting its bandwidth to 1 nm. At this condition, only three main lasing modes are transmitted through the filter. Conversely, the narrowest pulse of 720 fs is obtained with an unfiltered signal (full laser bandwidth) and after its propagation through the 450-m SMF.

In order to provide a more detailed analysis of our experimental results, the time-width of the optically-generated pulses is measured in terms of the bias current of the QD-PML FP laser for various BPF bandwidths. In this case, an unfiltered signal (no BPF) is also considered and the
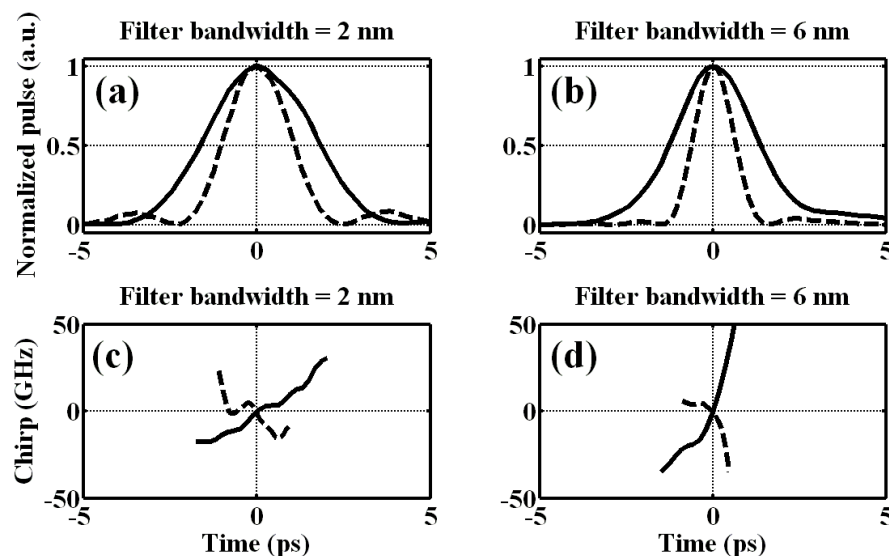

Fig. 4. Retrieved pulses shape ((a),(b)) and chirp ((c),(d)) from the QD-PML FP laser under test for filter bandwidths of 2 and 6 nm. Data in continuous line represent pulses before their propagation through the 450-m long SMF. Data in broken line represent pulses after their propagation through the 450-m long SMF. The laser is dc-biased at 350 mA.

450-m long SMF is connected at the input of the FROG system. As shown in Fig. 6, the pulse-width decreases as the dc-bias current increases. Considering for instance the unfiltered signal, which is represented by ($\diamond$), the pulse width is 2 ps for a dc-bias of 100 mA, whilst it is below 800 fs for a dc-bias ranging from 300 to 450 mA. This can be understood as a consequence of the number of lasing modes. To substantiate it, we can mention that at 100 mA the number of lasing modes is below 25 whilst at 350 mA, as depicted in Fig. 2(a), it is above 30. This leads to the implication that optical modes have all together a better quality of their respective phase locking at dc-bias conditions ranging from 300 to 450 mA than the phase locking obtained at lower dc-current supply. The pulse width trend is also observed when the band-pass optical filter is used, as illustrated in Fig. 6 for filter bandwidths of 3 nm (data in $\circ$) and 6 nm (data in $\square$). For a fixed value of dc-bias current, the pulse-width decreases as the BPF bandwidth increases.

This observation allows us to corroborate the influence of the number of modes and can be explained by considering the origin of the passive mode-locking mechanism. It has been demonstrated that the responsible process behind the passive mode-locking mechanism is the mode correlation between all the different modes oscillating into the laser cavity, largely dominated by four-wave mixing (for instance, see Ref. [7] for a discussion on quantum dash Fabry-Pérot lasers or Ref. [9] for multi quantum-wells distributed Bragg reflector lasers). Such an experimental demonstration has been obtained by measuring the RF-beating spectrum of three couples of modes along the laser spectrum. Thus, taking into account our results depicted in Fig. 6, a better correlation between all the optical modes is generated as the bias current is increased from 300 to 450 mA, resulting in a reduction of the pulse-width. Therefore, it seems to be possible controlling the width of the optically-generated pulses by varying the supplied dc-bias and/or externally selecting the number of modes.

4. Conclusion

Pulse generation in the sub-picosecond regime and at a repetition rate of 39.8 GHz has been experimentally investigated in a dc-biased passively mode-locked QD-FP single-section laser diode. Pulse width and chirp have been analyzed in terms of the number of optical modes passing through a band-pass optical filter. From our experimental results, a trend has been observed showing a reduction in the pulse width as either the number of optical modes selected by a band-pass filter is increased and/or as the dc-bias current increases. It is understood that this trend is driven by an improvement on the passive phase-locking mechanism. Furthermore,
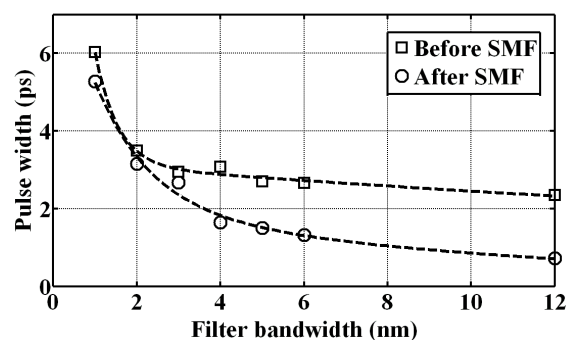

Fig. 5. Pulse width in terms of the filter bandwidth before ($\square$) and after ($\circ$) its propagation through a piece of SMF (QD-PML FP laser is dc-biased at 350 mA).
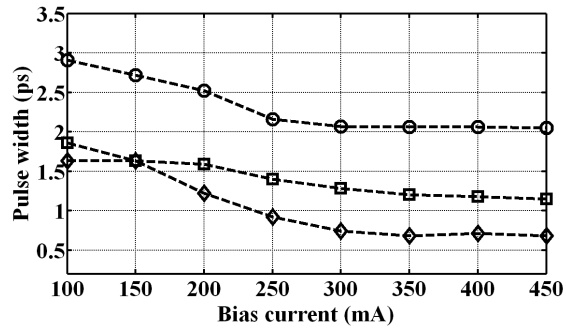
Fig. 6. Pulse width in terms of the dc-bias current supplied to the QD-PML FP laser for different filter bandwidths: 3 nm (○), 6 nm (□) and unfiltered pulses (◇).

by placing a 450-m SMF at the input of the FROG system, 720-fs pulses are obtained for an unfiltered optical spectrum. From these results, the generation of even shorter pulses can be envisaged by using single-section QD-PML FP laser diodes exhibiting a wider optical spectrum and presenting a similar passive mode-locking mechanism.